Patent Application of

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for

Fiber Optic Switch using Galvanometer-Driven X-Y Scanning

BACKGROUND

This invention relates to optical switches, and in particular to a fiber optic switch using X-Y scanning.

Optical switches are useful for a variety of applications, including fiber optic communications. In one design approach, optomechanical components are used to direct light from a desired optical input to a desired optical output. Conventional optomechanical switches include switches employing moving prisms, and switches employing moving fibers. While optomechanical switches can be relatively easy to manufacture, conventional optomechanical switches can suffer from limited switching speeds, reliability problems, undesirably high insertion losses, and interchannel crosstalk.

SUMMARY

The present invention provides an optical switch including an optical input for receiving a light beam; a rotatable-mirror x-y scanner optically coupled to the optical input, for selectively directing the light beam to one of a plurality of output paths; and a two-dimensional array of optical outputs capable of optical communication with the x-y scanner and aligned over an output surface, each of the optical outputs being aligned with one of the output paths so as to receive the light beam when directed by the x-y scanner onto the corresponding output path.

In the preferred embodiment, each optical input and output of the switch comprises an optical fiber collimator. The x-y scanner comprises a first mirror optically connected to the input collimator, for receiving the light beam from the input collimator; a first galvanometer coupled to the first mirror, for rotating the first mirror around a first axis so as to position the first mirror alternatively to any one of a plurality of first mirror positions; a second mirror optically connected to the first mirror, for receiving the light beam from the first mirror; and a second galvanometer coupled to the second mirror, for rotating the second mirror about a second axis perpendicular to the first axis, so as to position the second mirror alternatively to any one of a plurality of second mirror positions. Each of the output collimators is optically coupled to the second mirror, and is aligned with a ray corresponding to one of the first mirror positions and one of the second mirror positions. A light beam received at the switch input is directed to any one of the output collimators by rotating the first mirror and the second mirror to predetermined mirror positions corresponding to the selected output collimator.

The switch allows using relatively light moving parts, such as mirrors, which allow improved switching speeds. The galvanometer motors are capable of fast and precise positioning of the mirrors. Appropriate alignment and positioning of the optical input(s) and output(s) allow relatively low and uniform insertion losses.

DESCRIPTION OF THE FIGURES

Fig. **1** is a schematic diagram of an optical system including an optical switch of the present invention.

Fig. **2** shows a schematic isometric view of an optical switch according to the preferred embodiment of the present invention.

Fig. **3** shows an isometric view of a ray diagram illustrating the propagation of light through the switch of Fig. **2**.

Figs. **4-A** and **4-B** show schematic top (x-z) and side (y-z) diagrams, respectively, of the mirrors of the switch of Fig. **2**.

DETAILED DESCRIPTION

In the following description, the term "light beam" is understood to encompass light beams undergoing transformations over parts of theirs paths. The recitation of an element (e.g. an input) is understood to encompass at least one element.

The following description illustrates embodiments of the invention by way of example and not necessarily by way of limitation.

Fig. **1** shows a schematic diagram of an optical system **10** including an optical switch **20** of the present invention. Optical system **10** can be for example an optical communications system. Optical system **10** includes an optical source **12** and a plurality of optical receivers **18a-c** in optical communication with optical switch **20** over corresponding input and output optical links such as optical fibers **14**, **16**, respectively. Source **12** directs a light beam through input fiber **14** to optical switch **20**, and a selected one of receivers **18a-c** receives the light beam after passage through optical switch **20** and output fiber **16**. Optical switch **20** is controlled to selectively direct the light beam to any one of receivers **18a-c**.

Fig. **2** shows a schematic isometric view of optical switch **20**. Switch **20** includes an optical input such as an input fiber collimator **22**, for receiving an external light beam through an optical fiber **14** connected to collimator **22**. A galvanometer-driven, rotatable-mirror x-y optical scanner **24** is optically connected to input collimator **22**, for receiving the light beam **26** from collimator **22** and selectively directing light beam **26** onto one of a plurality of potential output directions or optical paths **30**. A two-dimensional array of optical outputs such as output fiber collimators **32** is arranged along an output surface facing x-y scanner **24**. Each collimator **32** is aligned with a corresponding optical path **30**, in order to selectively receive light extending over the corresponding optical path **30**. Each output collimator **32** is connected to a corresponding output fiber **16**. Packing output collimators **32** along two dimensions allows increasing the number of switch outputs for a given size of switch **20**.

The output surface is defined by the positions of output collimators **32**. In the preferred embodiment, the output surface coincides with the concave external surface of a support plate **33** having perpendicular apertures for holding collimators **32**. Each aperture extending through support plate **33** is locally perpendicular to the surface of plate **33**. Each aperture thus determines the orientation of its corresponding output collimator **32**. Each output collimator **32** is aligned with a corresponding direction or optical path **30** defined by light beam **26** as directed by scanner **24**. Scanner **24** selectively directs light beam **26** along any one of optical paths **30** to a corresponding selected output collimator **32**. The optical pathlength of light beam **26** through switch **20** is preferably substantially the same for any selected output collimator **32**. The alignment of each output

collimator **32** along its corresponding optical path **30** at an equal optical pathlength away from input collimator **22** allows for reduced and uniform insertion losses, and reduced interchannel crosstalk.

Scanner **24** comprises a first rotatable planar mirror (reflective surface) **34** optically connected to input collimator **22**, and a second rotatable planar mirror **36** optically connected to first mirror **34**. First mirror **34** and second mirror **36** are capable of independent rotation about mutually perpendicular axes. In the axis nomenclature **38** illustrated in Fig. **2**, first mirror **34** is capable of rotation about an axis parallel to the z-axis, while second mirror **36** is capable of independent rotation about the x-axis. Light beam **26** extends from input collimator **22** along the x-direction, and is reflected by first mirror **34** generally along the y-direction toward second mirror **36**. Second mirror **36** then reflects light beam **26** generally in the z-direction, toward a selected output collimator **32**. Each collimator **32** corresponds to a given first mirror position of first mirror **34** and a given second mirror position of second mirror **36**. Different collimators **32** can be sequentially selected by appropriately rotating first mirror **34** and second mirror **36** to the mirror positions corresponding to the collimator **32** to be selected.

First mirror **34** is coupled to a first galvanometer motor **40**, while second mirror **36** is coupled to a second galvanometer motor **42**. Galvanometers **40, 42** are capable of independently and continuously driving the rotational motions of mirrors **34**, **36**. Galvanometers **40**, **42** can be conventional galvanometers, for example as manufactured by Cambridge Technology, Cambridge, MA. Each galvanometer **40**, **42** includes a magnetic-based driving mechanism for rotating its corresponding mirror,

and a position detector for detecting the rotational position of the galvanometer **40**, **42**. A controller including a memory or storage device is coupled to galvanometers **40**, **42**, for controlling the rotation of mirrors **34**, **36** to predetermined calibrated positions corresponding to collimators **32**. The controller can be a general purpose computer or a dedicated control device.

Employing galvanometers for driving the motion of mirrors **34**, **36** allows improved accuracy and switching speeds for switch **20**. Mirrors **34**, **36** can have relatively low mass, which allows improved switching speeds, on the order of 1 ms with commercially available galvanometers. Moreover, the capability of galvanometers **40**, **42** to drive the motion of mirrors **34**, **36** continuously and accurately allows for improved insertion losses. For example, commercially available galvanometers can achieve angular resolutions of 15 microradians, which were observed to allow uniform insertion losses of less than 0.5 dB for each channel defined by an output collimator **32**.

The shape of the output surface defined by output collimators **32** is preferably defined by the condition that the optical path from input collimator **22** to any one of collimators **32** is constant. In a first approximation, the surface defined by the constant-optical-path condition is spherical, with a radius of curvature valued between R and R+d, wherein R is the distance between the second mirror **36** output collimators **32**, and d is the distance between the axes of mirrors **34**, **36**.

More precisely, the shape of the constant-optical-path output surface can be defined so as to account for the effects of the rotational positions of mirrors **34**, **36** on the corresponding

optical paths **30**. A precise definition of the surface corresponding to an exact constant-optical-path condition can be better understood with reference to Fig. **3**. Consider several rays **48** extending from a line **50** corresponding to the reflective surface of second mirror **36** (shown in Fig. **2**). Line **50** denotes the set of points along second mirror **36** that are hit by light as first mirror **34** is rotated. Rays **48** define a concave, constant-optical-path output surface **52**. The origin is denoted as **O**, while the intersection of the z-axis and output surface **52** defines a zenith point **E**. Line **50** coincides with the x-axis, and passes through origin **O**. The point **O'** denotes the midpoint of a virtual image curve **54**. Virtual image curve **54** lies along the y-z (x = 0) plane. Virtual image **54** is shaped as an arc of a circle centered at the origin **O**, and having a radius d. The radius d is equal to the distance between the axes of mirrors **34, 36**. The distance between origin **O** and zenith **E** is marked as R.

To derive the exact condition characterizing output surface **52**, consider an arbitrary point of coordinates (x,y,z) along output surface **52**, and a corresponding virtual image point of coordinates (0,y',z'). The point coordinates satisfy the conditions

$$y'^2 + z'^2 = d^2 \qquad [1a]$$

and

$$\frac{y}{y'} = \frac{z}{z'}. \qquad [1a]$$

These conditions can be re-written as

$$y' = -\frac{y}{\sqrt{y^2 + z^2}} d \qquad [2a]$$

and

$$z' = -\frac{z}{\sqrt{y^2 + z^2}} d \, . \qquad [2a]$$

If we now set the optical path s = R + d to be equal to

$$s = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2} \, , \qquad [3]$$

we can derive the equation characterizing constant-optical-path output surface **52** as

$$z = \sqrt{(\sqrt{(R + d)^2 - x^2} - d)^2 - y^2} \, . \qquad [4]$$

Eq. [4] can be re-written parametrically as a function of the rotational angles of mirrors **34**, **36**. Figs. **4-A** and **4-B** show schematic x-z and y-z plane views, respectively, of mirrors **34**, **36**. The angle θ_x denotes the angle between the two rays corresponding to the points (x, y, z) and (0, y, z), extending from mirrors **34, 36**. The angle θ_y denotes the angle between the z-axis and the projection on the y-z plane of the ray corresponding to the point (x, y, z) extending from mirror **36**. From Fig. **4-B**, it can be seen that

$$\frac{y}{z} = \tan\theta_y \, , \qquad [5a]$$

and

$$\frac{x}{z + d\cos\theta_y} = \frac{d\tan\theta_x}{d\cos\theta_y} \qquad [5b]$$

Eqs. [5a] and [5b] can be used to re-write eq. [4] parametrically as

$$\begin{aligned} x &= (R+d)\sin\theta_x \\ y &= [(R+d)\cos\theta_x - d]\sin\theta_y \\ z &= [(R+d)\cos\theta_x - d]\cos\theta_y \end{aligned} \qquad [6]$$

As is apparent to the skilled artisan, the exact constant-optical-path equations above are derived for free-space light propagation between input collimator **22** and output collimators **32**. If processing optics such as lenses are introduced in the optical path between input collimator **22** and output collimators **32**, the shape of the exact constant-optical-pathlength surface will change accordingly.

The preferred process of making switch **20** will now be described with reference to Fig. **2**. First, plate **33** and its perpendicular apertures are machined so as to correspond to a desired output surface. Plate **33**, input collimator **22**, and x-y scanner **24** are then mounted on a rigid frame made of a low-thermal-expansion-coefficient material such as Invar or stainless steel. The orientation and position of each output collimator **32** is adjusted for the corresponding x-y scanner mirror orientations, so as to minimize the insertion loss through each output collimator **32**. The angular positions of the x-y scanner mirrors corresponding to each output collimator **32** are then recorded in memory or storage, for recall during the subsequent operation of switch **20**.

As is apparent from the above discussion, the described devices and methods can be readily used to perform Mx1 switching, by reversing the direction of light propagation and appropriately controlling the x-y scanner of the switch. An

Mx1 switch then has an array of optical inputs and a single optical output. The x-y scanner of the switch is used to select one of multiple input light beams for transmission to the output.

A 1xN switch as described above can be used in combination with a similar Mx1 switch in order to make an MxN switch. The single fiber ports of the two switches are connected to each other along a fixed intermediate path. The first x-y scanner is then used to select one of a plurality of input light beams for transmission along the intermediate path. The second x-y scanner receives the selected light beam over the intermediate path, and transmits the light beam to a selected output. Each of the arrays of optical inputs and outputs is arranged over a surface characterized by a constant optical path relative to its respective x-y scanner.

Moreover, an array of M 1xN switches can be connected to an array of N Mx1 switches as described above to make an MxN cross-connect device. The outputs of the 1xN switches are connected to the inputs of the Mx1 switches. Each output of an array of N outputs of a given 1xN switch is connected to a corresponding input from a different Mx1 switch.

It will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. For example, various additional optical components such as lenses or mirrors can be used in a switch of the present invention. An additional focusing lens or lenses can be introduced between the input collimator and the x-y scanner, between the x-y scanner and the switch output array, or instead of the input collimator. Such additional optical components can alter the exact geometry of the output collimator surface corresponding to a constant optical path.

For example, if a cylindrical lens is placed between the second mirror and the output surface, with the cylindrical axis of the lens coinciding with the axis of rotation of the second mirror, the output surface will have a cylindrical curvature centered around the y-axis. Moreover, as is apparent to the skilled artisan, while the above description focuses primarily on an 1xN switch, the methods and devices described above can be readily used for Nx1 switches by reversing the direction of light propagation through the device, and using the described inputs as outputs and the described outputs as inputs. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.